Application of DRAINMOD-GIS to a Lower Coastal Plain Watershed

G. Fernandez, G. M. Chescheir, R. W. Skaggs, D. M. Amatya

Abstract. *This article reports a case study for applying DRAINMOD-GIS, a DRAINMOD-based lumped parameter watershed model, to Chicod Creek watershed, a 11100 ha coastal plain watershed in North Carolina that is not intensively instrumented or documented. The study utilized the current database of land use, topography, stream network, soil, and weather data available to state and federal agencies. Methods for collecting, evaluating, and formatting watershed data for model input are described. The study demonstrated that the lumped parameter model may be used to characterize the hydrology and water quality of Chicod Creek. Hydrology predictions were within 5% of the measured data. Predicted mean monthly nitrate-nitrogen (NO_3-N) loads compared well with the measured data. Mean annual delivery ratios of each field ranged from 81% to 99% with a watershed mean of 90%. Application of the model to evaluate the effects of changing land use is presented.*

Keywords. *Drainage, DRAINMOD, Nonpoint-source pollution, Water quality, Watershed-scale model.*

The impacts of excessive nitrogen (N) loading to streams are often manifested in the receiving waters (lakes, major rivers, or estuaries) at or below the outlet of the watershed. The nonpoint sources of N are usually well distributed among many fields or blocks within the watershed. Likewise, management practices that can be implemented to reduce N loading are distributed on a field-by-field basis throughout the watershed. In order to quantify the impacts of best management practices (e.g., land use changes and alternative management practices) on the N loading at the watershed outlet, simulation models are needed that can both predict the N loading at the field edge and the fate of N as it moves through the stream network to the watershed outlet. Various upland distributed parameter models, e.g., HSPF (Johansen et al., 1984), AGNPS (Young et al., 1987), SWAT (Arnold et al., 1998), and DWSM (Borah et al., 2002), exist for predicting the N loading at the outlet of watersheds. While these models are useful for upland conditions, the curve number method used to quantify runoff volume in these models is not applicable for the high water table soils of the lower coastal plain and other poorly drained watersheds. Accurately quantifying the drainage volume (both surface and subsurface) is essential for predicting N loading from a watershed. Since water table depth greatly affects outflow from high water table soils, a watershed model that considers drainage processes is necessary for predicting N loading from lower coastal plain watersheds (Skaggs et al., 2003; Amatya et al., 2004; Fernandez et al., 2005, 2006).

DRAINMOD-based watershed-scale hydrology and water quality models have been developed to predict N loading at the outlets of coastal plain watersheds (Amatya et al., 2004; Fernandez et al., 2002, 2005, 2006). Since these models simulate water table depth and runoff volume from individual fields distributed throughout a watershed, they can account for management practices and land use changes that occur on the field scale and predict the cumulative impact of these changes on N loading at the watershed outlet. The DRAINMOD-based models have accurately predicted drainage volume and N load at the outlet of a well-instrumented watershed near Plymouth, North Carolina. Fernandez et al. (2005) described two watershed-scale hydrology and water quality models that were used to evaluate the cumulative impacts of land use and management practices on downstream hydrology and nitrogen loading of a poorly drained coastal plain watershed in North Carolina. Field-scale hydrology and nutrient dynamics are predicted by DRAINMOD in both models. In the first model (DRAINMOD-DUFLOW), field-scale predictions are coupled to the canal/stream routing and in-stream water quality model DUFLOW, which handles flow routing and nutrient transport and in-stream water quality processes in the drainage canal/stream network. In the second model (DRAINMOD-W), DRAINMOD was integrated with a new one-dimensional canal and water quality model. The models were tested using data from a 2950 ha drained managed forest watershed in the coastal plain of eastern North Carolina. Both models simulated the hydrology and nitrate-nitrogen (NO_3-N) loading of the watershed acceptably. Simulated outflows and NO_3-N loads at the outlet of the watershed were in good agreement with the temporal trend for five years of observed data. Over a five-year period, total outflow was within 1% of the measured value. Similarly, NO_3-N load predictions were within 1% of the measured load. Predictions of the two models were not statistically different at the 5% level of significance.

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In a subsequent study, Fernandez et al. (2006) developed DRAINMOD-GIS, a watershed-scale, lumped parameter hydrology and water quality model based on DRAINMOD hydrology. The model integrates DRAINMOD and a lumped parameter water quality model with a simplified drainage canal routing and in-stream process submodel. The performance of the model was evaluated considering the uncertainties of the model inputs. The model was tested with measured data from a 2950 ha watershed used in the previous study. Model predictions were within 1% of both measured outflows and NO_3–N loads. Uncertainty analysis indicated that uncertainty in stream velocities, decay coefficient, and field exports significantly contributed to the uncertainty in the predicted outlet flows, loads, and mean watershed delivery ratio.

This article presents a case study of the application and validation of DRAINMOD-GIS to predict nitrate-nitrogen loading from a coastal plain watershed that is not intensively instrumented. The study utilized the current database of land use, topography, stream network, soil, and weather data readily available to consultants, state and federal agencies that would eventually use the models. The use of the model to predict the average nutrient delivery ratios for the various contributing areas in the watershed is demonstrated. The application of the model to evaluate effects of changing land use is also presented.

Watershed-Scale Model

DRAINMOD-GIS (Fernandez et al., 2006) couples the field hydrology model DRAINMOD (Skaggs, 1978) with a generalized spatially distributed canal routing model using a response function (Moussa, 1997). Field hydrology is simulated with DRAINMOD, and the drainage network routing is modeled with a kernel function using a Hayami function (Moussa, 1997) to characterize the time of travel in the flow path. The model uses a generalized approach to flow routing that considers spatially distributed inputs and parameters where drainage from contributing areas (non-overlapping) is considered separately instead of spatially averaged. DRAINMOD-GIS uses a two-parameter routing response function model with parameters that are related to flow time (advective velocity) and shear effects (dispersion) along the flow path.

In this model, DRAINMOD is used to simulate the water losses from contributing areas (under either controlled or conventional drainage). The water losses are then routed to the field outlets using an instantaneous unit hydrograph and eventually routed through a stream network to the watershed outlet using the response function. The model requires stream velocities along the flow path from contributing area to the watershed outlet as inputs. These velocities could be determined from simulations using mechanistic models (Amatya et al., 2004; Fernandez et al., 2005) or could be determined from flow records. For water quality, a first-order decay model (Preston and Brakebill, 1999; Fernandez et al., 2002; Amatya et al., 2004; Alexander et al., 2004) is used to characterize the attenuation of a water quality parameter as it travels along the flow path. Although the model can use a field water quality model such as DRAINMOD-NII (Youssef, 2003) to characterize drainage water quality at the field edge, concentrations based on values obtained from Deal et al. (1986) were used in this article. DRAINMOD-NII algorithms and inputs for predicting nitrogen and carbon dynamics have not yet been fully developed and tested for forested soils, so nitrate concentrations and loads at the field outlets were not simulated with a physically based model.

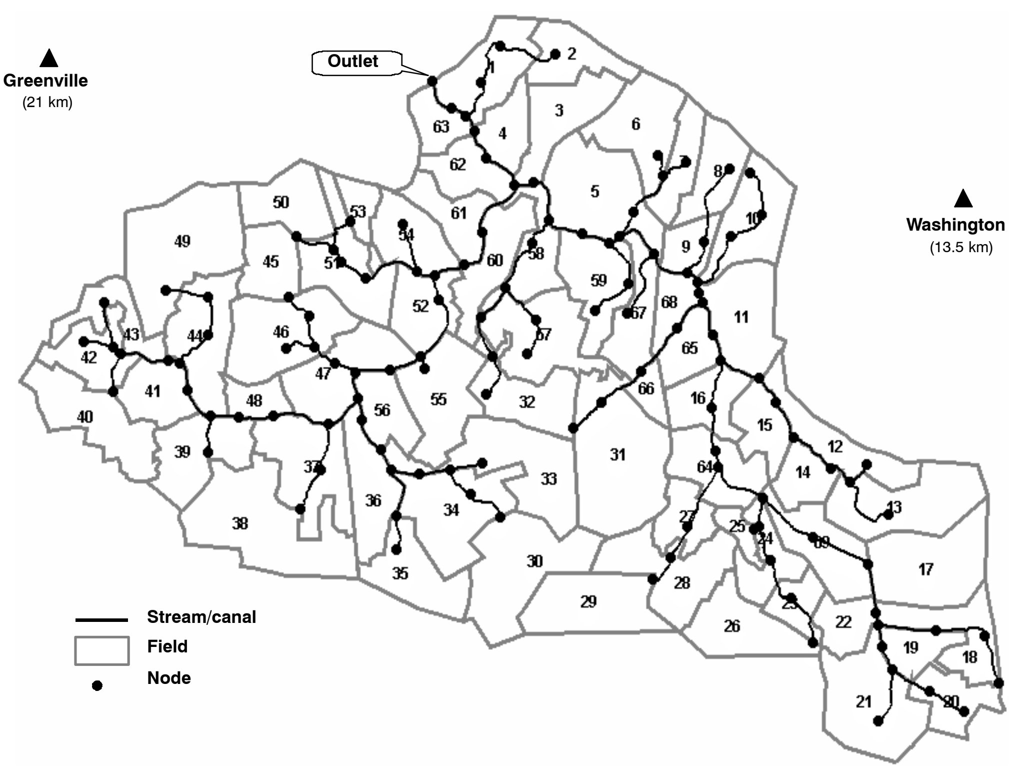

Figure 1. Schematic diagram of the Chicod watershed (not to scale).

Methodology

Site Description

The Chicod Creek watershed located near Greenville, North Carolina, was selected for the study. The watershed is 11100 ha in area and drains a combination of agricultural (55%) and managed and natural forest lands (45%) (fig. 1). A drainage improvement project was implemented in 1972 (USDA-SCS, 1971), which involved channelization and maintenance on the major streams and canal. Flow rates have been recorded at the outlet of the watershed from a gauging station operated by the U.S. Geological Survey (USGS) in cooperation with the North Carolina Department of Environment and Natural Resources (NCDENR) since 1975. Flow data were not available from 1989 to 1991. Daily nutrient monitoring was conducted for a full year from February 1993 to February 1994 and again from February 1997 to February 1998 by NCDENR.

Data Requirements

The model requires input data for soil properties, land use and management practices, stream network configuration, and weather data. Many of these data are available in Geographic Information System (GIS) formats, which are becoming the standard input for spatially distributed parameter models. However, these data need to be verified in the field since some errors may exist. The overall procedure for this study was: (1) to collect the existing GIS database for soils, land use, topography and stream network; (2) to make trips to the field to verify the data; (3) to correct data as needed; (4) to prepare the data for model input; (5) to make short-term simulations and calibrate the model based on measured available data; and (6) to make long-term simulations of the watershed. Outputs of the model include outflow and loads at the edges of individual fields and at the watershed outlet. Delivery ratios (the ratio of nutrient load at the field that is delivered to the watershed outlet) could then be calculated for each field in the watershed.

Initial Data Collection

Our initial data collection utilized the current GIS database of land use, topography, stream network, and soil data readily available to state and federal agencies. The land use and land cover data (LULC) were collected by USGS and compiled into 1:250,000 quadrangle tiles. Topography data were 1:24,000 digital elevation models (30 m DEM) compiled and made available through USGS. Stream network or hydrography data were in the form of 1:24,000 digital line graphs compiled and made available through USGS. Soils data were obtained from the Soil Survey Geographic (SSURGO) database compiled and made available through the USDA-NRCS. Digital road maps were obtained from the North Carolina Department of Transportation. We also obtained 1998 color infrared digital orthophoto quarter quadrangles (DOQQ, 1 m) that were compiled and made available by USGS and the North Carolina Center for Geographic Information and Analysis (NCCGIA).

All of the GIS coverages were converted to formats readable by GIS software. The data were transformed to the same projection (N.C. State Plane 1983/meters) as needed. Overlay maps of hydrography, roads, and DOQQ were printed for use during the field trips.

Field Trips

Field trips were conducted to verify watershed boundaries, check the accuracy of the stream network, and collect information on local management practices. On the initial trip, we met with the NRCS district conservationist and the manager of the local drainage district and obtained copies of the "as built" plans for the original drainage project and the current management plan. On a tour of the watershed, the drainage district manager assisted us in the corrections of our first estimate of the watershed boundaries. A subsequent trip was made to verify some land uses and watershed boundaries.

Preparation of Model Inputs

The stream network was discretized using the information available in the "as built" plans for the original drainage project. These plans provided channel location, channel dimensions, and channel bottom elevations. Channel dimensions and slopes have been preserved over time by a maintenance plan managed by the drainage district. The discretized network was consistent with the USGS hydrography data, but was less detailed. Some details of the USGS hydrography data were not consistent with our field observations. These inconsistencies were resolved through the assistance of Weyerhaeuser Company, a major landholder in the watershed.

The watershed was delineated into 69 fields according to general land uses (agriculture, managed forest, natural forest, and shrub land) as determined from the LULC data and USGS DOQQ coverage (fig. 1). Another factor considered in field delineation was the stream network. That is, the fields were delineated such that each field drained to an appropriate stream node. Field size ranged from 39 to 357 ha with an average of 161 ha (table 1). The 69 fields were overlaid with the SSURGO soil database to determine what soil series was most representative of each field. The number of soil series and the detail of their distribution shown in the soil maps were far greater than could be reasonably treated in the model; therefore, the 16 major soils series observed on the watershed were lumped into five representative soil types. The dominant soil in a block was chosen to represent the entire block.

Soil input data required by the DRAINMOD model is available from past research (Skaggs and Nassehzadeh-Tabrizi, 1986) for the five representative soil series (Bladen, Coxville, Goldsboro, Rains, and Wagram). The soils on the watershed were lumped into these five series according to soil texture, drainage class, permeability, and slope. The 16 dominant soils series (percent of watershed area) were lumped as follows: Leaf (15.5%) and Bladen (4.1%) into Bladen; Lenoir (12.6%), Coxville (6.7%), and Byers (4.5%) into Coxville; Exum (11.1%), Craven (9.4%), Goldsboro (3.7%), and Ocilla (1.2%) into Goldsboro; Lynchburg, (6.5%), Rains (6.4%), Bibb (2.2%), and Pantego (2.1%) into Rains; and Lakeland (4.4) and Wagram (1.3%) into Wagram.

Subsurface drains had been installed on many of the agricultural fields, but detailed information about the field drainage design and the current conditions of the drains was not known. Since all of the lands did not have improved drainage systems and some degradation may have occurred in the existing drainage systems, it was assumed that on average subsurface drainage intensity was less than optimum. DRAINMOD simulations were used to determine drain spacings for each soil that produced reasonable average annual yields (78% relative yield for corn), but subsurface drainage intensity was less than optimum. That is, drain spacings were greater than those for optimum yields. Optimum average annual corn yields are about 80% for drainage systems on these soils in eastern North Carolina, since yield losses due to drought stress occur as drain spacings decrease and drainage intensity increases (Skaggs et al., 2005).

Table 1. Distribution of land use and soils in the Chicod watershed used in the model.

Field	Soil	Land Use	Area (ha)	Field	Soil	Land Use	Area (ha)
1	Goldsboro	Agriculture	178.7	36	Blad	Agriculture	156.6
2	Blad	Agriculture	125.6	37	Goldsboro	Agriculture	231.4
3	Coxville	Agriculture	164.4	38	Rains	Natural forest	357.0
4	Goldsboro	Agriculture	95.5	39	Goldsboro	Agriculture	182.5
5	Coxville	Natural forest	266.2	40	Rains	Natural forest	212.4
6	Goldsboro	Agriculture	191.4	41	Goldsboro	Agriculture	115.8
7	Goldsboro	Agriculture	99.8	42	Coxville	Agriculture	130.1
8	Coxville	Agriculture	129.3	43	Blad	Natural forest	111.5
9	Coxville	Natural forest	75.0	44	Goldsboro	Agriculture	204.9
10	Blad	Managed forest	188.2	45	Rains	Agriculture	116.2
11	Coxville	Agriculture	197.1	46	Goldsboro	Agriculture	245.8
12	Goldsboro	Agriculture	155.3	47	Goldsboro	Agriculture	200.8
13	Blad	Managed forest	246.3	48	Rains	Agriculture	65.6
14	Blad	Agriculture	88.0	49	Rains	Natural forest	343.2
15	Wagram	Managed forest	103.9	50	Rains	Natural forest	142.9
16	Goldsboro	Agriculture	122.9	51	Goldsboro	Agriculture	197.4
17	Rains	Managed forest	255.7	52	Rains	Agriculture	134.4
18	Wagram	Managed forest	155.1	53	Rains	Natural forest	60.8
19	Wagram	Agriculture	84.8	54	Rains	Agriculture	138.8
20	Rains	Agriculture	109.0	55	Coxville	Agriculture	210.5
21	Rains	Agriculture	261.0	56	Goldsboro	Agriculture	106.4
22	Blad	Managed forest	83.6	57	Goldsboro	Agriculture	219.4
23	Blad	Agriculture	75.5	58	Goldsboro	Agriculture	123.5
24	Wagram	Managed forest	108.6	59	Goldsboro	Agriculture	175.6
25	Coxville	Agriculture	38.9	60	Goldsboro	Agriculture	151.5
26	Rains	Managed forest	175.4	61	Goldsboro	Agriculture	113.7
27	Coxville	Agriculture	101.3	62	Wagram	Agriculture	109.3
28	Coxville	Managed forest	264.9	63	Wagram	Managed forest	77.4
29	Blad	Agriculture	218.1	64	Coxville	Managed forest	236.2
30	Blad	Managed forest	292.7	65	Coxville	Natural forest	92.8
31	Coxville	Managed forest	306.2	66	Coxville	Agriculture	45.3
32	Coxville	Managed forest	154.8	67	Coxville	Natural forest	132.5
33	Blad	Natural forest	243.4	68	Coxville	Agriculture	72.1
34	Blad	Agriculture	225.1	69	Wagram	Managed forest	174.0
35	Blad	Managed forest	165.6				

Climate Data

Hourly rainfall and daily maximum and minimum temperature data were available for Greenville, N.C., from the National Climate Center. Daily rainfall is also available for the weather station in Washington, N.C. The Greenville and Washington stations are 21 km NNW and 13.5 km NNE from the center of the watershed. The average rainfall of the two stations was used for the simulations. While rainfall amounts and patterns recorded at these locations are very suitable for long-term simulations, errors in the magnitude of individual storms are likely, particularly for convective storms during the summer. These errors will be reflected in the storm-by-storm comparisons between simulated and observed outflows. The temperature data were used to calculate potential evapotranspiration by the Thornthwaite method, with monthly correction factors for eastern North Carolina (Amatya et al., 1995).

Model Simulations

The USGS maintains a gauging station at the outlet of the watershed. Flow rates recorded at this station were used to calibrate and validate the model. The model was calibrated with the 1992-1998 flow data and validated with the 1976-1986 flow data. The recent flow data were used for calibration, since two years of measured water quality data are available within this period. Water quality calibration used the available NO_3–N data from February 1993 to February 1994. The model was validated with data from February 1997 to February 1998. Hydrology calibration involves determining the field parameters for DRAINMOD (drainage intensity, surface storage, hydraulic conductivity) and routing variables (velocities and dispersion coefficient) to give the best fit to the monthly and annual observed outflows. Table 2 shows the calibrated DRAINMOD parameters used in the simulations.

Table 2. Calibrated DRAINMOD parameters.

Soil	Land Use	Drain Depth (cm)	Drain Spacing (m)	Surface Storage (cm)	Hyd. Cond.[a] (cm/h)
Blad	Agriculture	100	50	0.5	1.0
	Natural forest	10	200	5.0	5.0
	Managed forest	100	100	7.5	5.0
Coxville	Agriculture	100	50	0.5	5.0
	Natural forest	10	200	5.0	7.5
	Managed forest	100	100	7.5	7.5
Goldsboro	Agriculture	100	50	0.5	6.5
Rains	Agriculture	100	50	0.5	4.3
	Natural forest	10	200	5.0	15
	Managed forest	100	100	7.5	15
Wagram	Agriculture	100	70	0.1	15
	Natural forest	10	200	5.0	25
	Managed forest	100	100	7.5	25

[a] Hydraulic conductivity of the first layer.

DRAINMOD-GIS requires stream/canal velocities for routing flows from the field edge to the watershed outlet. The velocities used for model simulations were obtained from the measured data at the outlet of the watershed. These velocities were modified using the procedure described by Fernandez et al. (2006). The measured mean monthly velocities at the USGS gauging station at the outlet of the watershed range from 0.24 to 0.34 m/s with a mean of 0.28 m/s.

For water quality, using the limited measured data, the model was calibrated for the optimum decay coefficient and field edge NO_3−N concentrations given the predicted flow for each field in the watershed. Calibration was performed to match the monthly and cumulative NO_3−N loadings at the outlet of the watershed.

Input nitrogen load at the edge of each field was calculated by multiplying daily surface and subsurface flow volumes by export concentrations for surface and subsurface flow, respectively. The export concentrations for NO_3−N were calibrated starting from concentration values reported by Deal et al. (1986) for eastern North Carolina soils and conditions. The surface and subsurface concentrations were assumed to be constant for all storms for a particular soil and land use combination.

The export concentrations resulting from the calibrations of the model (table 3) were nearly half of those reported by Deal et al. (1986), which represented concentrations from small field plots (approx. 1 ha). The calibrated export concentrations were probably lower, since the simulated fields were larger (39 to 357 ha) than those represented by Deal et al. (1986) and some NO_3−N reduction could occur as the drainage water moves through field ditches and collector canals to the outlet of the large field.

The mass of NO_3−N delivered to the watershed outlet from each field was determined by using the time of travel along the flow path in the first-order exponential decay equation. The calibrated decay constant was 0.18 day^{-1}. The decay coefficient obtained is within the range of values experimentally determined by Appelboom (2004) for a forested canal and Birgand (2000) for an agricultural canal. Decay coefficients reported by Appelboom (2004), based on detailed experiments along a forested canal ranged from k = 0.07/d to 0.16/d. These values correspond to a mass transfer coefficient of ϱ = 0.064 m/d for depths of 0.4 to 0.9 m. The decay coefficient obtained by Birgand (2000) for an agricultural canal ranged from 0.2/d to 1.6/d, corresponding to a mass transfer coefficient of ϱ = 0.3 m/d. In the application of SPARROW (Preston and Brakebill, 1999) for nitrogen loading in the Chesapeake Bay watershed, the calibrated instream loss coefficient ranged from 0.07/d (discharge > 1000 cfs) to 0.76/d (discharge < 200 cfs).

Total NO_3−N load at the watershed outlet was the sum of the delivered loads from all of the fields. Monthly and cumulative flows and NO_3−N loads for both the calibration and validation periods were compared to the measured flows and NO_3−N loads.

Table 3. Nitrate-nitrogen export concentrations used for calibrating the model.

	Agriculture Corn – Soybean		Forest and Shrubland	
Soil	Subsurface (mg/L)	Surface (mg/L)	Subsurface (mg/L)	Surface (mg/L)
Blad	2.1	0.5	0.3	0.3
Coxville	2.3	0.5	0.3	0.3
Rains	2.3	0.5	0.3	0.3
Goldsboro	2.6	0.5	0.3	0.3
Wagram	2.6	0.5	0.3	0.3

The calibrated model was then used to simulate the outflow and nitrate loads for a 30-year period from 1975 through 2004. Statistics quantifying the annual flow and NO_3−N load at the watershed outlet over the 30-year period were summarized. The NO_3−N predictions included the loads delivered from each field to the watershed outlet. These values were also summarized, and an average delivery ratio was determined for each field. The delivery ratio for field A was calculated as the NO_3−N load delivered at the watershed outlet from field A divided by the NO_3−N load from field A deposited in the stream at the field edge. That is, a delivery ratio of 0.5 for a given field would mean that, on average, 50% of the NO_3−N leaving the field arrives at the outlet.

In addition to predicting the long-term hydrology and NO_3−N loads for the watershed for the current conditions, simulations were conducted to determine the impacts of alternative land and water management practices. The effects of land use changes were determined through a long-term simulation using the calibrated parameters. Results were summarized in statistics and probability distributions for annual outflows and nitrogen load.

Results and Discussion

Flow

DRAINMOD-GIS simulations of the watershed predicted monthly outflow rates that were comparable to those measured by the USGS gauging station. The temporal trend predicted by the model closely agreed with the observed data, as shown in figures 2 and 3. Some differences in monthly flows would be expected, since the rainfall record used for the simulation was collected 22 km (Greenville) and 13.5 km (Washington) from the center of the watershed. On average, the mean monthly error was less than 0.1 mm during the calibration period and slightly higher at 1.5 mm during the validation. For the 7-year calibration period, the prediction error of the cumulative outflow is less than 1% with a mean monthly absolute error of 11 mm. The prediction error for the cumulative outflow during the 11-year validation period is 5% with a similar mean monthly absolute error of 14 mm. These prediction errors are much better than the prediction errors of the simulation of an intensively tile-drained watershed in central Iowa using the modified SWAT model (SWAT-M; Du et al., 2005).

Tables 4 and 5 show comparisons of the measured and predicted annual flows for the calibration and validation periods, respectively. During the calibration period, the predicted annual flows are within ±7% of the measured flows. For the validation period, prediction errors ranged from −16% (1977) to 73% (1986). The overprediction in 1986 is due largely to the overprediction of the monthly flow for August (>200%). Such overprediction may be due largely to the distance of the rainfall stations from the watershed. Because of the distance of the stations from the center of the watershed, the assumed rainfall may not be entirely representative of the local conditions.

Statistics of the comparison between the predicted and measured monthly flows indicate that the model performed reasonably well. Table 6 summarizes the statistics of the comparisons

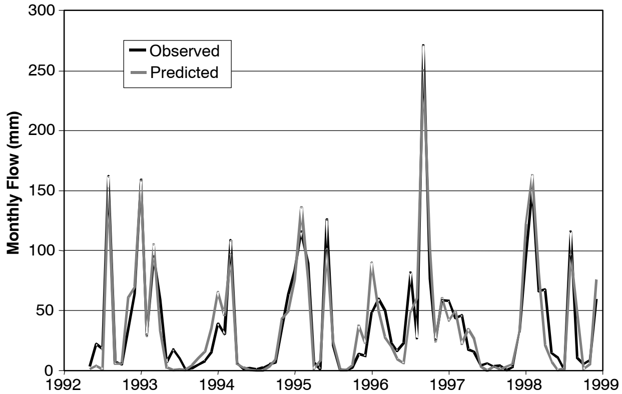

Figure 2. Predicted and measured monthly outflows at the outlet of Chicod watershed for 1992 to 1998 (calibration period).

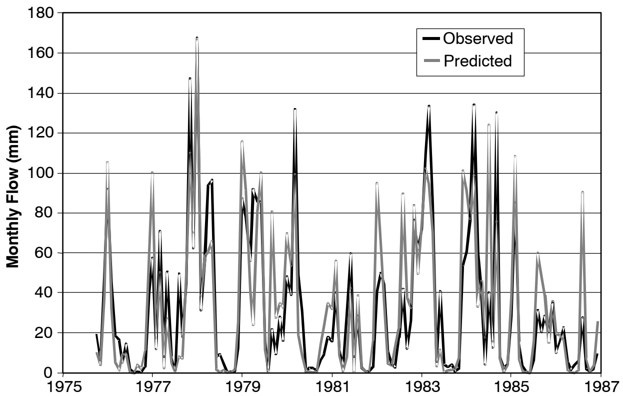

Figure 3. Predicted and measured monthly outflows at the outlet of Chicod watershed for 1976 to 1986 (validation period).

between the predicted and measured outflows for the calibration and validation periods. The Nash-Sutcliffe (N-S) coefficient for monthly values of 0.9 for the calibration period is considered to be acceptably good (Van Liew et al., 2003). The validation period has an N-S coefficient at 0.68, which is within the satisfactory range of 0.36 to 0.75 (Motovilov et al., 1999). Similarly, the Pearson correlation coefficients are high (>0.8), which indicates satisfactory goodness of fit between the predicted and measured monthly outflows.

Table 4. Summary of measured and predicted annual outflows at the outlet of the Chicod watershed during the calibration period.

Year	Measured (mm)	Predicted (mm)	Prediction Error (%)
1992	316	299	−5.4
1993	408	394	−3.4
1994	300	320	6.7
1995	472	488	3.4
1996	762	748	−1.8
1997	233	221	−5.2
1998	607	623	2.6
1992-1998	3097	3093	−0.2

Table 5. Summary of measured and predicted annual outflows at the outlet of the Chicod watershed during the validation period.

Year	Measured (mm)	Predicted (mm)	Prediction Error (%)
1976	238	240	0.8
1977	531	448	−15.6
1978	486	421	−13.4
1979	575	641	11.5
1980	340	325	−4.4
1981	205	206	0.5
1982	388	530	36.6
1983	514	470	−8.6
1984	571	590	3.3
1985	275	369	34.2
1986	107	184	72.0
1976-1986	4230	4424	4.6

Nitrate-Nitrogen

Measured nitrate-nitrogen concentrations for February 1993 to February 1994 were used to calibrate the water quality component of the model. The measured data from February 1997 to February 1998 were used for validation. Minimal calibration was conducted, and it involved primarily the determination of the optimum decay coefficient and field edge NO_3−N concentrations that would give the minimum error in predicted cumulative NO_3−N load at the outlet of the watershed. Figures 4 and 5 show comparisons of the predicted monthly NO_3−N loads for the watershed for the calibration and validation periods, respectively.

During the calibration period, the model overpredicted the cumulative nitrate-nitrogen load at the watershed outlet by

Table 6. Summary of statistics of goodness of fit of the monthly predicted watershed outflows.

Statistics for Flow during Outflow Calibration and Validation	Calibration (1992-1998)	Validation (1976-1986)
Observed mean (mm)	38.7	32.0
Predicted mean (mm)	38.6	33.5
Mean deviation (mm)	−0.1	1.5
Mean abs. deviation (mm)	11.2	13.6
RMSE (mm)	15.6	20.8
Percentage error (%)	<−0.1%	4.7%
Nash-Sutcliffe coefficient	0.90	0.68
Pearson correlation coefficient	0.95	0.84
Statistics for Flow during the NO_3−N Load Calibration and Validation	**Calibration (Feb. 1993 to Feb. 1994)**	**Validation (Feb. 1997 to Feb. 1998)**
Observed mean (mm)	24.5	32.4
Predicted mean (mm)	26.7	35.8
Percentage error (%)	9.0%	10.5%
Nash-Sutcliffe coefficient	0.77	0.92
Pearson correlation coefficient	0.88	0.96

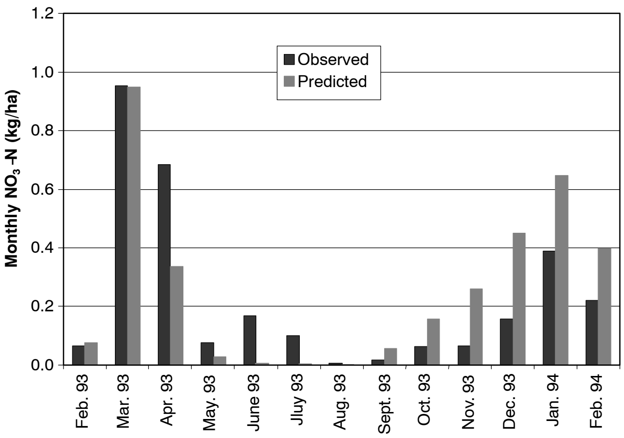

Figure 4. Predicted and measured monthly nitrate-nitrogen load at the outlet of Chicod watershed for the calibration period.

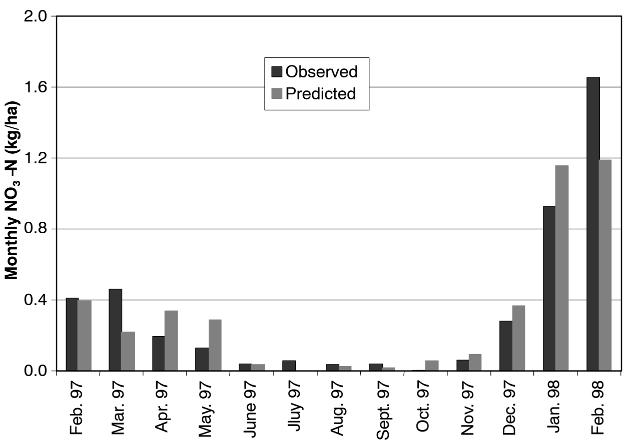

Figure 5. Predicted and measured monthly nitrate-nitrogen load at the outlet of Chicod watershed for the validation period.

13.4%. A much lower prediction error of less than 5% was obtained during the validation period. On the average, the monthly error in the predicted load is 0.03 kg/ha and 0.01 kg/ha for the calibration and validation periods, respectively. The calibrated mean monthly absolute error is 0.13 kg/ha. A slightly lower average monthly absolute error of 0.12 kg/ha was obtained for the validation period. The errors in the prediction were likely due to the errors in the prediction of the outflows. Table 6 shows that for the 13-month (Feb. 1993 to Feb. 1994) calibration period, the cumulative outflow was overpredicted by 9%. A similar overprediction of 10% for the 13-month validation period (Feb. 1997 to Feb. 1998) was obtained. Although there may be errors in the assumed export concentrations (assumed to be constant for all storms during the calibration and validation periods) and the decay coefficient, errors in the flow prediction may have contributed greatly to the errors in load predictions.

Table 7 summarizes statistics of comparison between the predicted and observed monthly NO_3–N loads. Similar to the statistics of the monthly outflows, the N-S coefficient of 0.60 for the calibration period is within the satisfactory range. For the validation period, the N-S coefficient is much better at 0.86, indicating that the mean square error of prediction is only 14% of the variance of the observed data.

Table 7. Summary of statistics of goodness of fit of the monthly predicted nitrate-nitrogen load.

Statistic	Calibration (Feb. 1993 to Feb. 1994)	Validation (Feb. 1997 to Feb. 1998)
Observed mean (kg/ha)	0.228	0.330
Predicted mean (kg/ha)	0.259	0.344
Mean deviation (kg/ha)	0.031	0.014
Mean abs. deviation (kg/ha)	0.133	0.123
RMSE (kg/ha)	0.174	0.172
Percentage error (%)	13.4%	4.2%
Nash-Sutcliffe coefficient	0.60	0.86
Pearson correlation coefficient	0.81	0.93

Table 8. Summary of annual statistics of a 30-year simulation to determine effects of land use.

Statistic	50% Agriculture[a]	75% Agriculture	100% Agriculture
Flow			
Mean (mm)[b]	378 a	410 b	437 c
Standard dev.	175	169	165
Standard error	32	31	30
% Difference		8.5%	15.6%
Load			
Mean (kg/ha)[b]	3.61 a	4.69 b	5.68 c
Standard dev.	1.27	1.51	1.79
Standard error	0.23	0.28	0.33
% Difference		29.9%	57.3%

[a] Current condition.
[b] Means followed by different letters are significantly different at the 5% level.

Using a similar simulation model, Amatya et al. (2004) obtained prediction errors for an intensively instrumented managed forest watershed in eastern North Carolina that were higher than the errors obtained in this study. Application of DRAINMOD-GIS for the same watershed used by Amatya et al. (2004) yielded improved agreement between simulated and measured flows and nitrogen loads (Fernandez et al., 2006).

Long-Term Simulations

Table 8 shows a summary of the statistics of the 30-year simulation. Predicted annual outflow varied from 126 to 756 mm, with a mean of 378 mm (standard error of 32 mm). Predicted annual NO_3–N load at the watershed outlet varied from 1.43 to 6.24 kg/ha/year, with a mean of 3.61 kg/ha/year (standard error of 0.23). The predicted outflows and loads are distributed as shown in figures 6 and 7. The graphs show the percentage of time that a given outflow or load will be exceeded or equaled. For example, at 90% probability, the annual outflow and load under the current condition will be greater than or equal to 164 mm and 1.94 kg/ha/year, respectively.

Because of the in-stream losses, the predicted NO_3–N load at the watershed outlet was about 10% less than the cumulative load leaving the individual fields. This corresponds to a mean watershed delivery ratio of 90%. In-stream losses depend on the time-of-travel of the water particle as it moves from the field edge to the outlet. Thus, the NO_3–N load delivered from fields at the head of the watershed farthest from the outlet will be a smaller percentage of that leaving the field edge than that delivered from fields close to the outlet. This is indicated graphically in figure 8, which shows that the mean delivery ratio varies from about 0.80 to 0.99 on the Chicod watershed.

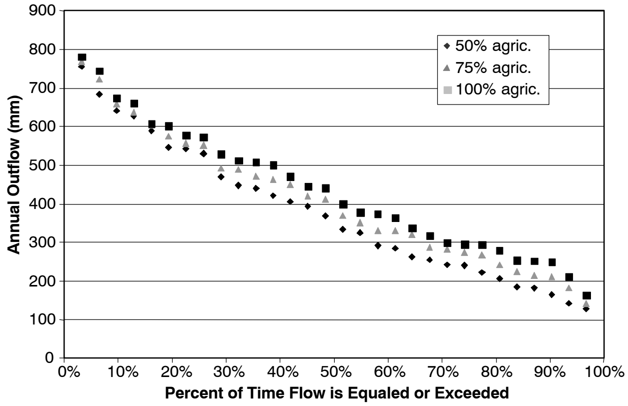

Figure 6. Distribution of annual watershed flow.

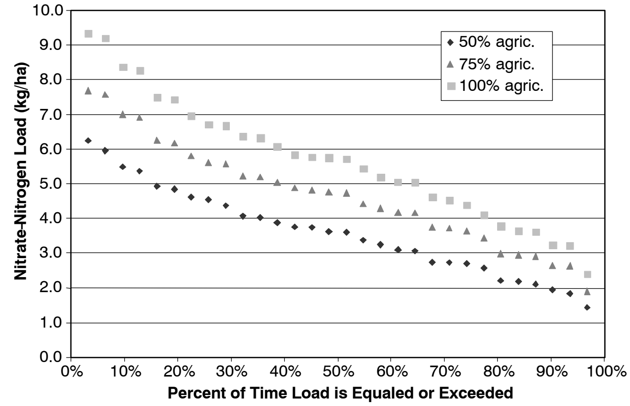

Figure 7. Distribution of annual nitrate-nitrogen load.

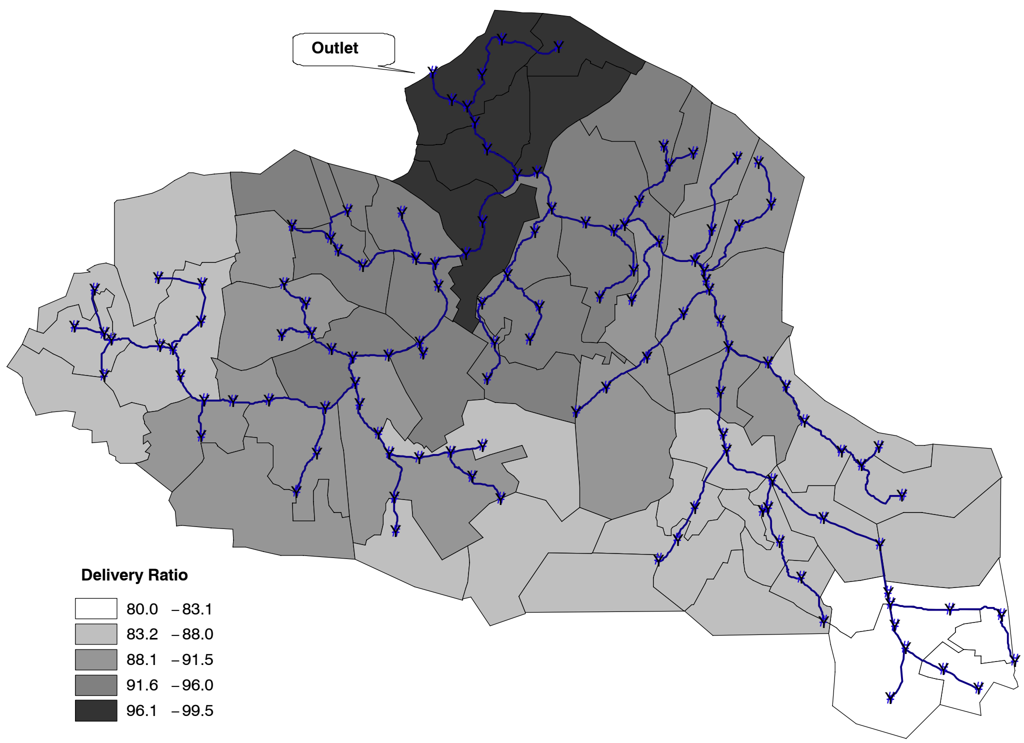

Figure 8. Distribution of delivery ratios.

Knowledge of the spatial distribution of the delivery ratio is important for decision makers. With a map of the delivery ratio or the delivery ratio normalized by the field load, managers can make informed decisions about locating best management practices (BMP) for reducing N losses and restoration projects within a watershed. As shown in the map of the delivery ratios, a BMP that would have the greatest impact on the outlet load could be implemented in fields near the outlet or adjacent to the main drainage canals, which have the highest delivery ratios.

Table 7 and figures 6, 7, and 9 also summarize the effects of changing land use in the watershed. From the current condition of about 50% agriculture, watershed outflow increased by 9% if the percentage of agriculture was increased to 75%. Converting all lands to agriculture increased the outflow by 16%. The changes in outflow resulted in corresponding increases in loads delivered to the outlet. Outlet load increased by 30% (for 75% agriculture) and 57% (for 100% agriculture).

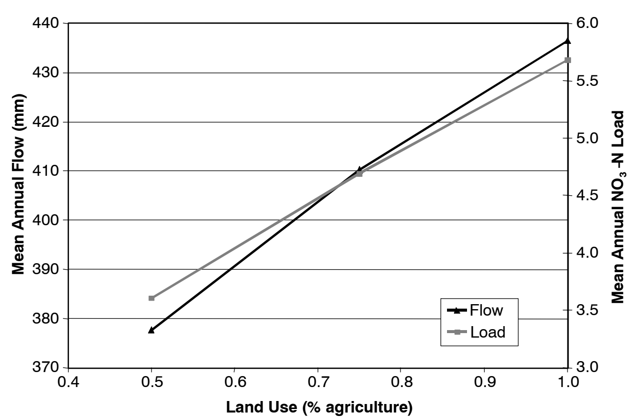

Figure 9. Effects on changing land use on watershed outflow and load.

Summary and Conclusions

This article documents a case study for using a DRAINMOD-based, watershed-scale model to predict nitrate loading from a coastal plain watershed in North Carolina. The current, readily available database for land use, topography, stream network, soil, and weather data was used to predict the hydrology and nitrate loading from the watershed on a day-by-day basis for a 30-year period of climatological record.

The DRAINMOD-based model, which links DRAINMOD field hydrology and a spatially distributed routing model using a response function, accurately predicted the drainage volume and the cumulative nitrate-nitrogen load at the outlet of the Chicod watershed. Although there were errors in predicting the daily hydrograph peaks, the model reasonably predicted the monthly drainage volume. Accurate prediction of the drainage outflows is important in predicting nitrate loads. With minimal calibration of the water quality parameters, the model predicted nitrate loads at the outlet of the watershed that were in good agreement with the observed loads for both the calibration and validation periods.

The study also demonstrated the application of the model for evaluating the effects of changing land use on watershed load and outflow. An important output of the model is a graphical display of the delivery ratios for each field in the watershed. This ratio indicates the percentage of field load that is delivered to the outlet of the watershed. For management purposes, knowledge of the spatial distribution of the delivery ratios is important for determining where to implement best management practices that would have the greatest impact.

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